Estimating BFOR on HV Transmission Lines Using EMTP and Curve of Limiting Parameters

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Abstract--**This paper presents a method for estimating the backflashover rate (BFOR) on high voltage (HV) transmission lines. The proposed method employs a state-of-the-art model of HV transmission line (TL) for backflashover analysis, assembled within the EMTP-ATP program—with EMTP running in batch mode—to construct the curve of limiting parameters (CLP). The probability of backflashover occurrence at a particular TL tower is obtained by computing the volume under the surface of the probability density function of the bivariate log-normal statistical distribution (of lightning current parameters), bounded by the CLP in the coordinate system of lightning-current amplitude and wave-front duration. This probability, in combination with the estimated number of direct lightning strikes to TL towers, obtained from the application of the electrogeometric model, provides the associated BFOR, assuming it is further normalized on the basis of 100 km-years. The usage of the proposed method is demonstrated on a typical HV transmission line. A sensitivity study for estimating the BFOR with the proposed method is provided as well.**

Keywords: **Backflashover, Bivariate statistical distribution, BFOR, EGM, EMTP, Lightning, Transmission line.**

I. Introduction

HIGH voltage (HV) transmission lines are exposed to lightning strikes, where only direct lightning strikes (to shield wire(s), phase conductors and tower tops) are of engineering concern. Direct lightning strikes to shield wire(s) and tower tops can provoke a flashover of the transmission line (TL) insulation, where the strikes to the tower tops are more significant in producing insulator flashovers (and statistically speaking more probable) then the strikes to mid-spans. The rate at which this is to be expected, per 100 km-years of transmission line, is termed the backflashover rate (BFOR). The BFOR is important for estimating the outage rates of TLs due to lightning, for designing the HV substation overvoltage protection (in terms of the incoming overvoltage emanating from the backflashovers on neighbouring TL towers incident to the station), and for shielding of TLs using the surge arresters.

The BFOR on TLs has been treated by analytical and numerical methods, with analytical methods extensively described by the IEEE WGs [1], [2] and CIGRE WGs [3]. Numerical approach to the transient analysis of transmission line lightning surges necessitates detailed, and often quite sophisticate, models of the TL components, some of which exhibit non-linear behaviour, frequency-dependence, etc. The IEEE WGs and CIGRE WGs offer extensive guidelines for representing transmission line elements (and beyond) for numerically simulating lightning surge transients [4]-[6]. Particular simulation details concerning the BFOR analysis on HV transmission lines can be found in e.g. [7]-[15], with numerical analysis usually carried out using the well-known ElectroMagnetic Transients Programs (EMTP), e.g. [16]-[18].

The method of estimating BFOR on HV transmission lines, proposed in this, paper aims to take into the account following aspects of the phenomenon: TL route keraunic level(s); statistical depiction of lightning-current parameters (including statistical correlation between the parameters); electrogeometric model (EGM) of the lightning attachment process (assuming only vertical strokes); frequency-dependence of TL parameters, corona effects, and electromagnetic coupling between conductors; tower geometry and surge impedance; tower footing impulse impedance (with soil ionization if present); lightning-surge reflections from adjacent towers; non-linear behaviour of the insulator strings flashover characteristic; TL span length; statistical distribution of lightning strokes along the TL span; power frequency voltage.

This transmission line model is constructed within the EMTP-ATP software package and used to derive a so-called curve of limiting parameters (CLP), [19], [20]. Based on the curve of limiting parameters—obtained from the EMTP simulation runs—probability of backflashover occurrence at a particular TL tower (featuring certain geometry and soil resistivity) can be estimated. This is performed by computing (numerically) the volume under the surface of the probability density function of the bivariate log-normal statistical distribution (of lightning current parameters), bounded by the curve of limiting parameters in the coordinate space of lightning-current amplitudes and wave-front durations. This probability, in combination with the estimated number of direct lightning strikes to transmission line towers (itself obtained by means of applying the EGM to TL tower), provides the associated BFOR, assuming it is further normalised on the basis of 100 km of line length per year.

II. Lightning current parameters

Lightning current is depicted with an amplitude, wave-front duration and wave-tail duration. In HV transmission line studies, predominantly negative downward lightning strikes are of engineering interest; hence, only these will be presented hereafter, [21], [22].

It is well-known that lightning-current parameters each individually follow a log-normal distribution, in which case the probability density function (PDF) of the statistical variable can be given by the following expression [22]:

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$$f(x) = \frac{\exp\left[-\frac{(\ln x - \ln x_\mu)^2}{2\sigma_{\ln x}^2}\right]}{\sqrt{2\pi}\cdot x\cdot \sigma_{\ln x}} \quad (1)$$

where x_μ represents the median value and $\sigma_{\ln x}$ represents the associated standard deviation of the lnx. However, there has been found a statistically significant correlation between the lightning-current amplitudes and wave-front steepness. This necessitates usage of the joint (i.e. bivariate), as well as conditional, probability distributions in their treatment. The bivariate log-normal probability density function, in case of the lightning current amplitude (I) and wave-front duration (t_f), can be described by the following relation [22]:

$$f(I, t_f) = \frac{\exp\left[-\frac{f_1 - f_2 + f_3}{2\cdot(1-\rho_c^2)}\right]}{2\pi\cdot I\cdot t_f\cdot \sigma_{\ln I}\cdot \sigma_{\ln t_f}\cdot \sqrt{1-\rho_c^2}} \quad (2)$$

with:

$$f_1 = \left(\frac{\ln I - \ln I_\mu}{\sigma_{\ln I}}\right)^2 \quad (3)$$

$$f_2 = 2\rho_c \cdot \frac{\ln I - \ln I_\mu}{\sigma_{\ln I}} \cdot \frac{\ln t_f - \ln t_{f\mu}}{\sigma_{\ln t_f}} \quad (4)$$

$$f_3 = \left(\frac{\ln t_f - \ln t_{f\mu}}{\sigma_{\ln t_f}}\right)^2 \quad (5)$$

where I_μ, $\sigma_{\ln I}$ represent median value and standard deviation of lightning current amplitudes, $t_{f\mu}$, $\sigma_{\ln tf}$ represent median value and standard deviation of the lightning current front duration, and ρ_c is the coefficient of correlation between them.

Table I provides parameters of the depicted statistical distributions of lightning currents, which will be utilised hereafter [21], [22]. This is in order to account for the fact that there are differences between lightning data statistics provided by different researchers, and in order to demonstrate its influence on the backflashover occurrence rates. Duration of the lightning current wave-tail is in all cases fixed at 77.5 μs, considering its negligible influence in producing TL backflashover.

TABLE I
LIGHTNING CURRENT STATISTICAL PARAMETERS

Lightning set	Amplitude		Front duration		Corr.
	I_μ	$\sigma_{\ln I}$	$t_{f\mu}$	$\sigma_{\ln tf}$	ρ_c
Original	31.1	0.484	3.83	0.550	0.47
Alternative	34.0	0.740	2.00	0.494	0.47

III. MODEL FOR TL BACKFLASHOVER ANALYSIS

An EMTP-ATP model of the transmission line for lightning surge transient simulation (including backflashover analysis) has been thoroughly studied and widely published, e.g. [6], [8]-[10]. The model generally consists of several components: TL phase conductors and shield wire(s), including spans, line terminations and power frequency voltage; TL tower; tower footing impedance; insulator string flashover characteristic; lightning current and lightning-channel impedance.

Transmission line phase conductors and shield wire(s) are modelled using a distributed-parameters, untransposed, frequency-dependent, multiphase, transmission line, featuring sophisticate JMarti TL model [18]. Five spans of the transmission line, at each side of the tower being struck by lightning, are modelled in this way. After the fifth span, at each side of the struck tower, additional length of the transmission line is modelled in the same way (to eliminate travelling-wave reflections), and the line model is terminated by an ideal, grounded, power-frequency, three-phase, voltage source.

The steel-lattice towers of HV transmission lines are usually represented as a single-conductor, distributed-parameter, frequency-independent, transmission lines. The single value of the tower surge impedance is computed from the analytical expressions which depend on the tower configuration and can be found in [4], [8]. The velocity of the surge propagation along the steel-lattice tower is assumed to be equal to the speed of light in free space (although some authors assume somewhat lower value).

The lightning-struck TL tower grounding, assuming it is concentrated (i.e. not extending beyond cca 30 m), can be modelled in accordance with guidelines provided in [4] and implemented in EMTP-ATP by means of the MODELS language [18]. Following equation is used for the purpose:

$$R_i = \frac{R_0}{\sqrt{1 + I_t/I_g}} \quad (6)$$

where R_0 is the tower grounding resistance at low-frequency and low-current values, I_t is the lightning current through the tower grounding, and I_g is the lightning current level which determines the soil ionization inception. It can be obtained from: $I_g = \rho E_0 / \left(2\pi R_0^2\right)$ where E_0 is the soil ionization electric field gradient and ρ is soil resistivity. Groundings of the adjacent TL towers are modelled with a simple resistance.

The insulator strings flashover characteristic is a non-linear function of the applied impulse voltage and it is usually modelled in the EMTP-ATP by means of the voltage-controlled TACS switches. The flashover characteristic itself is programmed using the MODELS language [18]. Insulator strings flashover behaviour is depicted by the so-called leader progression model. There are several variants of this model, e.g. see [15], but the particular one used in this paper is based on the solution of the following differential equation [4]:

$$\frac{d\ell}{dt} = k\cdot u(t)\cdot \left[\frac{u(t)}{d_g - \ell_\ell(t)} - E_0\right] \quad (7)$$

where: d_g is the insulator strings length, $\ell_\ell(t)$ is the leader length, u(t) is the actual (absolute value) voltage on the insulator strings, and k, E_0 are constants which are found to be dependent on the type of the insulator. The differential equation is solved during the EMTP simulation, by means of the MODELS language, for the length of the leader at each simulation time-step. If this length attains or exceeds the length of the insulator strings, the associated TACS switch is closed, signifying the occurrence of the insulator flashover.

A direct lightning strike to the TL tower top is within the EMTP-ATP modelled as an ideal current source in parallel with the resistance, the value of which represents the lightning-channel surge impedance. The Heidler current source type is used in this paper [18], in combination with a 400 Ω resistance.

IV. NUMBER OF DIRECT LIGHTNING STRIKES

Number of direct lightning strikes to transmission lines is traditionally estimated from the electrogeometric model of lightning attachment [7]. According to the EGM of lightning attachment to TLs—and considering only vertical strikes—the number of direct lightning strikes to phase conductors and shield wire(s) depend on their exposure areas, which are determined in terms of the lightning striking distance and tower geometry. According to EGM theory presented in [7], following expression for estimating the number of direct lightning strikes to shield wire(s) can be obtained:

$$N_{gw} = 2LN_g \cdot \int_0^{I_m} D_g(I) f(I)\, dI + + 2LN_g \cdot \int_{I_m}^{\infty} D_g^{'}(I) f(I)\, dI + LN_g S_g \tag{8}$$

where: $N_g = 0.04 T_d^{1.25}$ in (km^{-2}year^{-1}) is the annual average ground flash density T_d is the long-term average annual number of thunderstorm days); f(I) is the probability density function of the lightning current amplitudes distribution; L is the transmission line length; S_g is the distance between shield wires; I_m is the maximum shielding failure current; $D_g(I)$ and $D'_g(I)$ are exposure distances for the shield wire(s) as a function of lightning current amplitudes. The maximum shielding failure current and exposure distances for the shield wire(s) depend on the EGM that is being applied to the TL geometry. If the TL route traverses through terrains with different keraunic levels, the route is then split into sections having different keraunic levels and equation (8) is solved for each of the sections separately.

The maximum shielding failure current can be determined from the following expression [7], [8]:

$$I_m = \left(\frac{r_{gm}}{A}\right)^{1/b} \tag{9}$$

$$r_{gm} = \frac{(h+y)/2}{1-(r_c/r_g)\cdot \sin\left(\tan^{-1}\frac{a}{h-y}\right)} \tag{10}$$

where r_c and r_g depict striking distances to phase conductors and ground surface, respectively; h is the height of the shield wire(s) on the tower; y is the height of the phase conductor(s) at the tower and *a* is the length of the tower arm(s) carrying the phase conductor(s). Exposure distances for the shield wire(s) can be, in accordance with the EGM model, determined from the following expressions [7]:

$$D_g = r_c \cdot \cos\left(\tan^{-1}\frac{a}{h-y} - \beta\right) \tag{11}$$

$$D_g^{'} = \begin{cases} \sqrt{r_c^2 - (r_g - h)^2} & r_g \geq h \\ r_c & r_g < h \end{cases} \tag{12}$$

with

$$\beta = \sin^{-1}\frac{\sqrt{a^2 + (h-y)^2}}{2r_c} \tag{13}$$

Lightning strikes are not uniformly distributed along the TL span length. If one considers only lightning strikes to TL tower tops (and their near-vicinity), which is often the case with the BFOR analysis, then the expression (8) needs to be corrected with the appropriate coefficient which takes into the account the actual statistical distribution of lightning strikes along the TL span length. This coefficient equals 0.6 in accordance with the analysis provided in [7], [23].

V. Curve of Limiting Parameters

The curve of limiting parameters brings into relationship incident lightning currents with the critical currents for backflashover occurrence [7], [19], [20]. It is derived from the EMTP simulation runs and subsequently applied for estimating the probability of backflashover (BFO) occurrence. Namely, by computing (numerically) the volume under the surface of the PDF of the bivariate log-normal statistical distribution (of lightning current parameters), bounded by the curve of limiting parameters (in the coordinate space of lightning-current amplitudes and wave-front durations), one obtains the probability of BFO occurrence at a particular TL tower (featuring certain geometry and soil resistivity), [7]. The central aspect of this approach, hence, lays in the construction of the curve of limiting parameters.

The computational procedure for obtaining CLP can be decomposed into three separate stages: (i) pre-processing, (ii) numerical simulation of the backflashover occurrence, and (iii) post-processing, with first and third stages implemented in a purposefully developed computer program. In the first stage, a preparation of the input data is carried out, as will be explained in a moment. The second stage is implemented by means of the EMTP running in batch mode, with interventions on its input and output files carried-out between simulation runs with the developed computer program. This stage produces a curve of limiting parameters. In the third stage, computation of the BFOR probability and BFOR per 100 km-years is performed, using the data provided by the numerical simulations (i.e. CLP) and additional computations of the number of lightning strikes to transmission line. The algorithm for constructing the curve of limiting parameters is graphically depicted in Fig. 1.

The outer loop runs across lightning current wave-front durations and for each front-time the inner loop uses a type of bisection search method to find the minimum value of the lightning-current amplitude (i.e. critical current) for which a flashover is still possible (in accordance with the EMTP model)—which establishes a single point on the curve of limiting parameters (see Fig. 1). Any lightning current amplitude above this "critical" value (for that particular wave-front duration) is certain to produce a backflashover. The complete run of the outer loop, hence, yields a curve of limiting parameters—defined in a point-by-point fashion, in the coordinate space of wave-front duration and amplitude (the same coordinate space where the surface of the bivariate PDF of the log-normal distribution of lightning current parameters exists).

The shaded block in Fig. 1 embodies three distinctive actions, performed successively within the double-loop. First, an "atp" model file, initially created with the ATPDraw [18], is manipulated in order to structure a "dat" file—featuring the appropriate lightning wave-front duration and amplitude values. Second, EMTP is invoked (through a batch file) and executed using a dedicated OS command. Third, newly-created "lis" file is examined for the onset of flashover (considering the fact that the position of the TACS switch of the insulator flashover model has been broadcast).

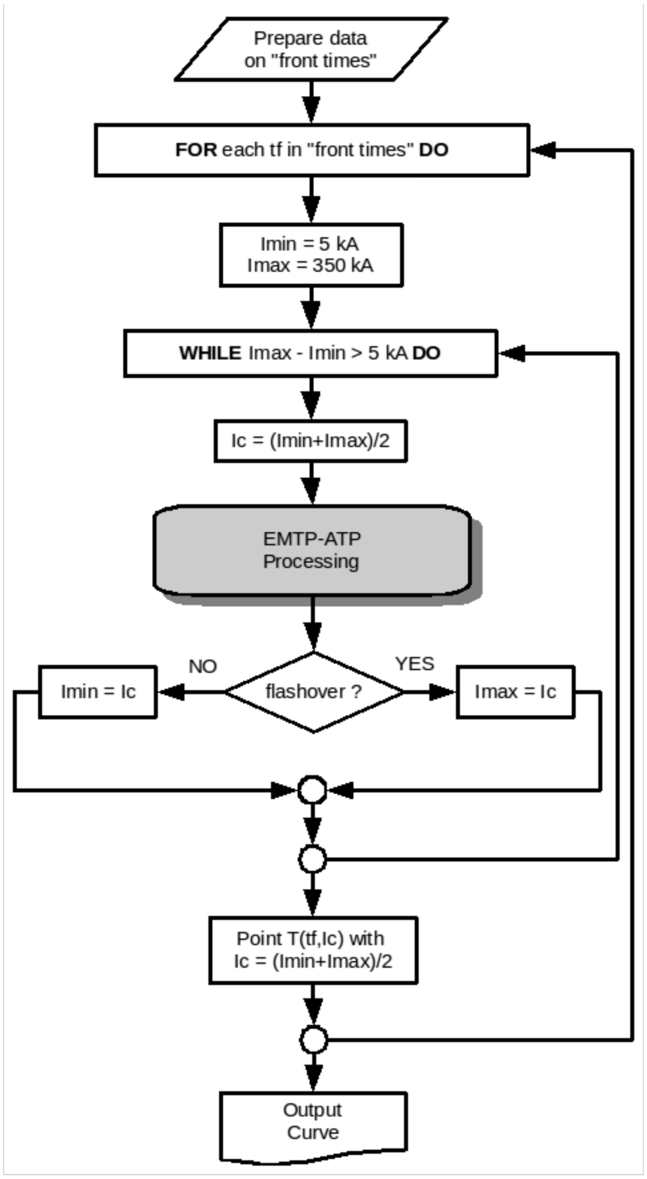

Fig. 1. Algorithm for constructing the curve of limiting parameters

Lightning current wave-front times are chosen starting at 0.1 µs and ending at 32 µs, because this range contains above 99.99 \% of all values, in accordance with the appropriate log-normal distribution. From 0.1 µs to 10 µs the range is divided in 0.1 µs increments, from 10 µs to 20 µs in 0.2 µs increments, and above that value in 0.3 µs increments. This gives in-total 190 individual values of lightning wave-front times for the outer loop. The inner loop is bounded between 5 kA and 350 kA, because this range contains above 99.99 % of all values, in accordance with the appropriate log-normal distribution. The inner loop usually needs about 7-8 runs for achieving the prescribed tolerance, which yields around 1500 runs in-total, for constructing the curve of limiting parameters. This is the most time-consuming part of the computation, which takes about 10 minutes of CPU time on modern PC architectures.

Once the curve of limiting parameters is constructed, the volume under the bivariate PDF of the log-normal distribution of lightning current parameters—bounded by this curve—is numerically computed, yielding the BFO probability for a particular TL geometry and tower footing impedance. Using this probability, the BFOR can be estimated as follows:

$$BFOR = 0.6 \cdot N_{gw} \cdot P_B \tag{14}$$

with P_B, as already stated, obtained from

$$P_B = \iint_{\Omega} f(I, t_f)\, dI\, dt \tag{15}$$

where Ω defines a region in the coordinate system of lightning-current amplitude and wave-front duration, "above" the curve of limiting parameters.

VI. Test Case TL and Sensitivity Analysis

Presented method for estimating the BFOR on HV transmission lines will be demonstrated on a typical single-circuit 110 kV TL, featuring vertical conductor configuration and steel-lattice towers. Tower geometry is typical for wind pressures between 750-1500 N/m^2, with individual spans of 350 m, typical for 750 N/m^2 wind pressure and 65 N/m^2 of maximum allowed conductors tensile strength. Average ground flash density is taken at 1 km^{-2}year^{-1} for the entire TL route. Tower height equals 25 m, with distance from the top to the highest arm of 3 m, distance between tower arms of 2 m; top console length of 2.5 m, middle console length of 3 m and bottom console length of 3.5 m. Phase conductor DC resistance 0.114 Ω/km with 10.95 mm diameter, shield wire 0.304 Ω/km with 8mm diameter. Insulator string length equals 0.9 m.

Fig. 2 presents curves of limiting parameters, obtained for the TL at hand, for several different values of TL tower footing impedances.

Tower footing impedances used on all of the figures in this paper are low-current and low-frequency values, obtained from the tower grounding system configuration and soil resistivity. They feature prominently in the IEEE model of the TL tower grounding system, [4]. It is clear from this figure that the minimal values of lightning-current amplitudes (i.e. critical currents) that can still provoke a backflashover increases as the wave-front duration is increased. This is expected. In fact, for very long wave-front times the associated amplitudes attain the value of 350 kA (or more), meaning that the flashover is extremely improbable, regardless of the tower footing impedance.

It could also be deduced from this figure that the BFO probability increases with the increase of the tower footing impedance, which is again expected [7]. Namely, the superposition of the bivariate PDF of the log-normal distribution onto the Fig. 1 enables the curves of limiting parameters to clearly reveal the region Ω, which features prominently in computing the BFO probability. This is graphically depicted for the original set of lighting-current parameters in Fig. 3.

By introducing curves of limiting parameters in (15), with (2) and (3)-(5), one obtains the BFO probability. Furthermore, by using this value and computing the expected number of lightning strikes to TL from (8), while employing a particular EGM for that purpose, equation (14) yields the backflashover rate.

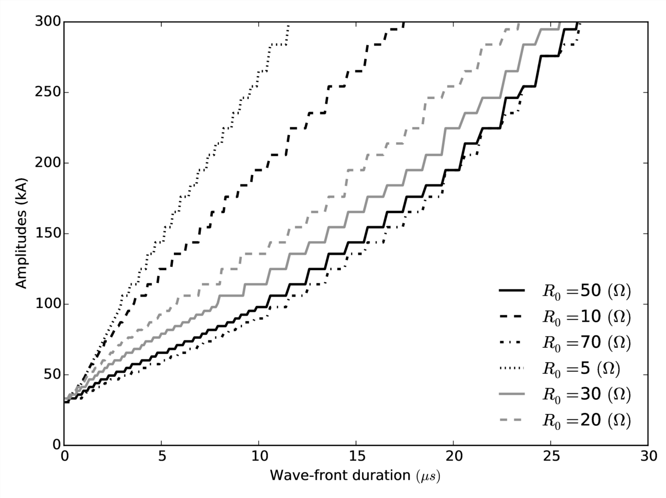

Fig. 2. Curve of limiting parameters obtained for several different values of tower footing impedances

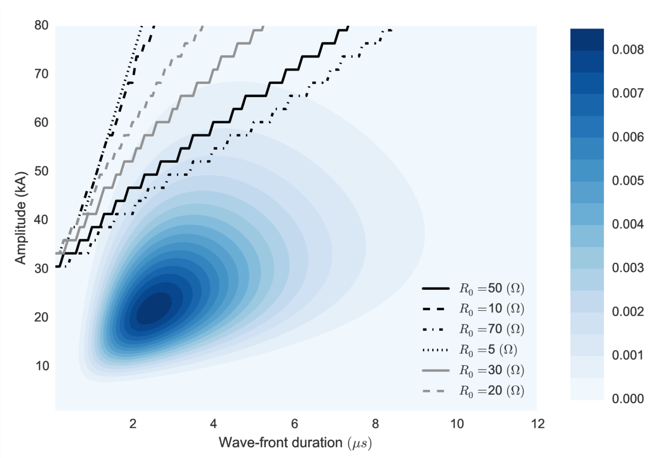

Fig. 3. Superposition of the bivariate PDF of log-normal distribution of lightning currents with the curves of limiting parameters

Fig. 4 presents the BFO probability and BFOR per 100 km-years for the TL at hand, obtained from the Brown and Whitehead EGM and the "original set" of lightning data.

The application of different possible EGM models would yield somewhat different BFOR per 100 km-years, although the BFO probability remains the same. The reason is in the fact that different EGMs provide different estimated numbers of direct lightning strikes for the same TL geometry. Fig. 5 provides BFOR per 100 km-years for the TL at hand, obtained using several different EGMs, [7], and original set of lightning-current parameters.

It is important to emphasize that the provided results accounted for the statistical correlation between lightning-current amplitude and wave-front duration of the original set of lightning data.

The statistical correlation, as it turns out, is important in establishing the BFO probability. This is quite evident from the Fig. 6, depicting the BFO probability for the TL at hand, obtained with three different values of the correlation coefficient and the original set of lightning-current parameters.

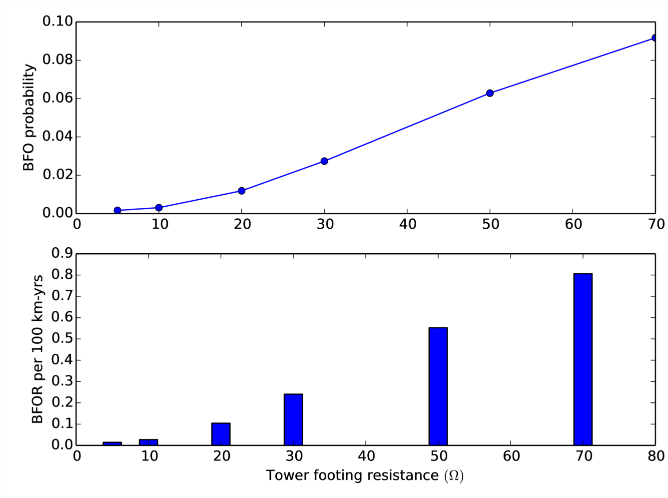

Fig. 4. BFO probability and BFOR per 100 km-years using the Brown and Whitehead EGM and original set of lightning-current parameters

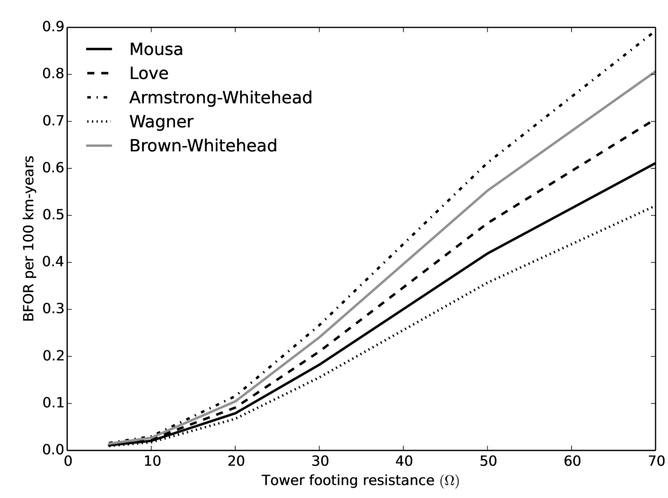

Fig. 5. BFOR per 100 km-years using several different EGMs and original set of lightning-current parameters

It is evident that by neglecting the correlation between lightning-current amplitude and wave-front duration one increases the BFO probability and, hence, increases the expected BFOR per 100 km-years.

Moreover, in case of employing the "alternative set" of lightning data (Table I) and Brown and Whitehead EGM for the TL at hand, different BFO probability and, hence, BFOR per 100 km-years, has been obtained—as can be seen in Fig. 7, particularly if compared with Fig. 4. This is expected since the median value of the wave-front duration is lower for the alternative set, which skews the bivariate PDF of the associated log-normal distribution to the "left" region of the coordinate space, providing larger volume under this function once it is bounded by the curve of limiting parameters (which stays the same).

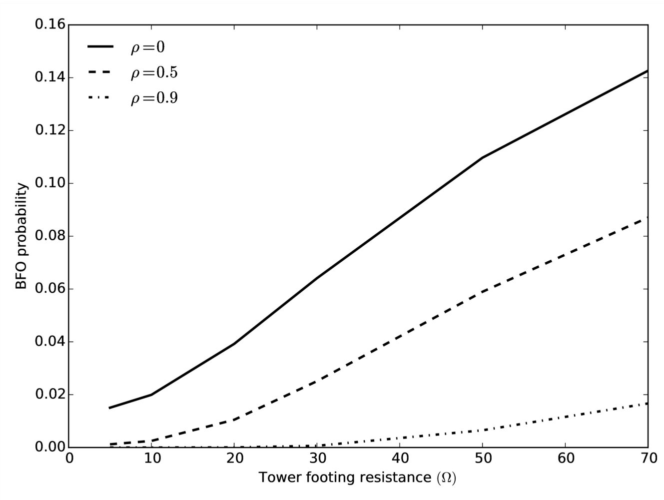

Fig. 6. BFO probability with three different levels of statistical correlation between lightning-current parameters

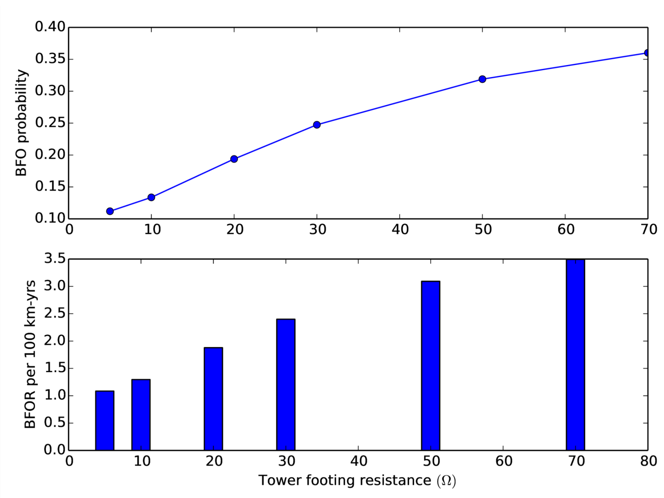

Fig. 7. BFO probability and BFOR per 100 km-years using the Brown and Whitehead EGM and alternative set of lightning-current parameters

Furthermore, in order to briefly provide for a sensitivity analysis, one can make account of the several different possible treatments of various TL model components—most notable of which are the models of insulator flashover characteristic and tower grounding transient impedance. For that purpose, several different model combinations are provided, along with lightning parameters from both data sets (Table I). Therefore, Table II systematically presents several different combinations of TL component models and lightning-current parameters.

Simple switch model depicts a TACS switch which is closed (signifying flashover) when the voltage across the insulator string exceeds a value of 605d, where *d* is the length of the insulator string. The IEEE model, as already stated in Section III, assumes concentrated tower grounding system and current-dependence due to soil ionization. Simple tower (grounding) resistance assumes that the tower footing surge impedance is equal to its low-current and low-frequency value and does not change during simulation.

TABLE II
SEVERAL DIFFERENT COMBINATIONS OF TL MODEL COMPONENTS AND LIGHTNING PARAMETERS

Model	Flash. char.	Tower grnd.	Lgtn. data set
Model A	Leader prog.	IEEE model	Original
Model B	Simple switch	Simple resist.	Original
Model C	Leader prog.	Simple resist.	Original
Model D	Simple switch	IEEE model	Original
Model E	Leader prog.	IEEE model	Alternative

For example, Fig. 8 displays the curves of limiting parameters, obtained for the "Model C" of the TL at hand, for several different values of TL tower footing impedances and the original set of lightning data. The curves are superimposed on the bivariate PDF of the appropriate log-normal distribution. A visual comparison of Figs. 2 and 8 reveals that the CLPs in the latter case will produce larger BFO probabilities with the same lightning-current parameters, which is expected.

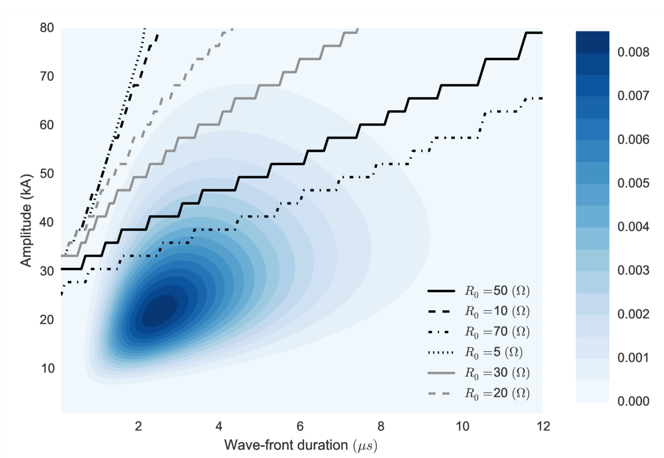

Fig. 8. Curve of limiting parameters obtained for Model C and original set of lightning-current parameters

Fig. 9 presents final results obtained with different model combinations from the Table II, in terms of the expected BFO probability, revealing significant differences. Further differences are to be expected with these models, in terms of BFOR per 100 km-years, due to the differences emanating from applying different EGMs.

It is evident from the foregoing analysis that the employment of a simple TL tower grounding model increases the BFO probability. Even greater influence is exhibited by using the simplified model of the insulator string flashover characteristic. Further differences are to be expected if other (sophisticate) models of the TL tower grounding systems are to be employed, especially if the tower grounding system cannot be considered concentrated (e.g. if it has counterpoise wires which extend beyond some 30 m from the tower base). Also, particularly notable influence emanates from the statistical parameters of lightning currents, with statistical correlation featuring prominently.

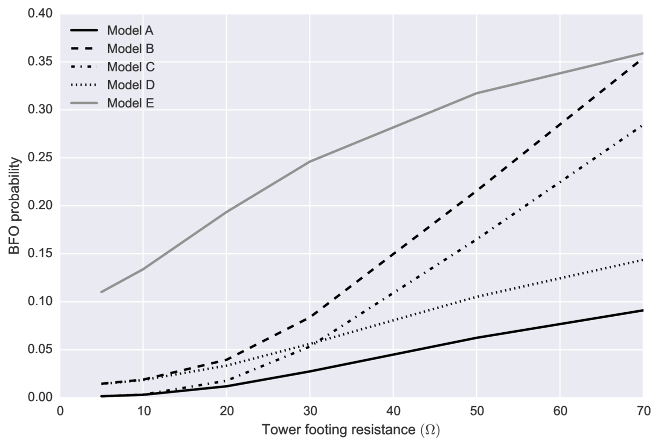

Fig. 9. BFO probability for different combination of TL model components and lightning-current parameters

VII. Conclusions

This paper presented a method for the analysis of the backflashover occurrence rates on HV transmission lines. As far as the authors are informed, this particular approach to the CLP construction and subsequent application has not been published thus-far, although the CLP has been used before (and always derived in analytical form). Majority of the influential factors affecting the BFO probability and BFOR per 100 km-years on HV transmission lines have been accounted for. This method can be applied equally-well on a specific portion of the TL, on the particular TL as a whole (i.e. accounting for different keraunic levels), or as a means of estimating TL generic BFOR per 100~km-years.

The sensitivity analysis, although brief, reveals several factors influencing the expected BFOR on TLs and their importance. At the top of this list are, certainly, the lightning-current parameters incident to transmission lines. Here, a possibility of the statistical realisation of the combination of high lightning-current amplitudes with short front-durations features prominently in increasing the expected BFO probability (and BFOR per 100 km-years), making the statistical correlation between them an important influential factor.

The presented method yields computational results (i.e. constructs the curves of limiting parameters and numerically solves associated single and double integrals) in a short execution time, which makes it ideal for the large number of different simulation runs, testing for different scenarios and TL model component influences.

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